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Relationships Between Chlorophyll Density and Ocean Radiance As Measured by U2/OCS: Algorithms, Examples and Comparison

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RELATIONSHIPS BETWEEN CHLOROPHYLL DENSITY AND OCEAN RADIANCE AS MEASURED BY U2/OCS: ALGORITHMS, EXAMPLES AND COMPARISON

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ABSTRACT

An ocean-atmosphere radiative transfer process computation method which is suitable for determining lower boundary ocean albedo and other radiation components from spectral measurements of upwelling radiance taken from a high altitude platform is described. The method has been applied to a set of ocean color scanner data taken from slope water of the South Atlantic Bight to determine the influence of chlorophyll—a pigments in the sea on the ratio of upwelling radiance to downwelling irradiance as a function of wavelength. The resulting chlorophyll concentrations are compared with measurements made by ships stationed along the flight path. The derived relationships between 'the blue-green ratio' and chlorophyll concentrations from this study in regression coefficients a and b for C (chloro. conc.) = $a(I^{w}_{431\ nm}/I^{w}_{550\ nm})^{b}$ are 3.0 and - 2.4 respectively.

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RELATIONSHIPS BETWEEN CHLOROPHYLL DENSITY AND OCEAN RADIANCE AS MEASURED BY U2/OCS: ALGORITHMS, EXAMPLES AND COMPARISON

INTRODUCTION

During each spring of the three year period between 1979 and 1981, NASA's U2 aircraft carrying an Ocean Color Scanner (OCS) was flown over a designated ocean area approximately 180 km due east of Jacksonville, Florida. The purpose of these aircraft flight experiments was to observe the radiometric characteristics of phytoplankton blooms which frequently occur in this region of the South Atlantic Bight (SAB). The experiments permitted some tentative judgments to be made about the physical oceanographic processes occuring in the area. The 3-year study which combined ship, buoy, and remote sensor measurements coupled with the output of modelling analysis has shown us that:

a. The occurence of the plankton patches in this region of the SAB is associated with the vertical inflow into the surface Ekman layer[1]. The advection of the nitrogen rich deep layer onto the upper surface is associated with horizontal stress as well as the vorticity. Thus, one would expect to see a variety of chlorophyll patterns as evidenced in the OCS chlorophyll pattern images of the area in 1979 to 81. (See figure 1 of this article and figure 7 of Ref. 3).

b. A great portion of eddy-forced upwelling nutrients is used by phytoplankton and the resultant phytoplankton blooms probably are important in the food chain structure of this outer southeastern shelf. The oceanographic aspect of this SAB study has been reported elsewhere[2].

The aircraft flight experiment had an important investigative goal to obtain a suite of hydrographic water column data which could be used for verifying the aircraft data analysis. The surface research group collaborated in collecting correlative surface truth measurements during the time of the aircraft overpass. Detailed planning and coordination between ship and aircraft crews insured one of the flight paths passed directly over the ship operating in the vicinity of a suspected dynamic feature.

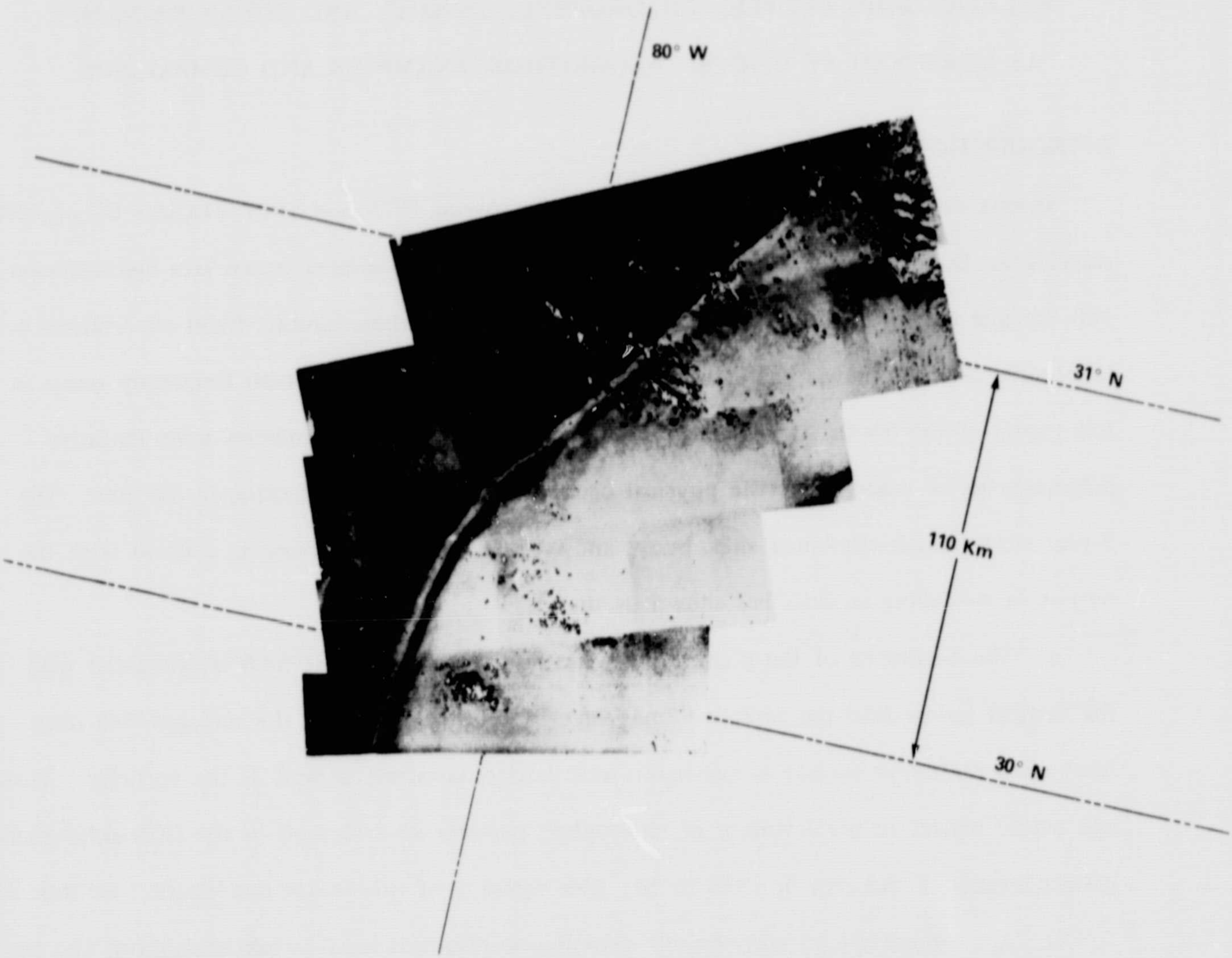

Figure 1. U2/OCS image of April 16, 1980, off the coast of Jacksonville, FL. The original data were processed and enhanced for ocean chlorophyll gradient expression. The dark filament along the western edge of the Gulf Stream is an upwelling of nitrate rich water and has high chlorophyll content 1.5 to 2.0 mg/M^3.

A study report on the subject of radiometry and remote sensing based on the 1979 pre-Georgia Bight Experiment (GABEX) has been published earlier[3]. But the authors felt that the 1979 data represented only an initial set of data. Additional data acquired in 1980 and 1981 contain different sets of the atmospheric and solar illumination conditions and significant improvements have been made on analysis algorithms. Thus it is the aim of this article to update our findings based on additional field data and to provide additional information which is in sequel to the previous work. There is a strong need for a reliable ocean color analysis method which can be used for processing satellite data.

FIELD DATA COLLECTION

Figure 2 depicts the U2/OCS study area for the years 1979-1981. This area is along the western edge of the Gulf Stream which is delineated by strong thermal and chlorophyll concentration fronts. Mesoscale circulation features which are manifested in the chlorophyll pattern as patches and striations, are often located along the frontal zone. The front usually follows the 200-m isobath line. On the day of the U2 aircraft flight during each of these three years, oceanic research ships were located in the study area. The operations of the research vessels were under the direction of personnel from Skidaway Institute of Oceanography. Investigators from this institute collected most of the hydrographic data used in the U2/OCS studies. Chlorophyll concentrations were determined at discrete ship stations using laboratory analysis techniques. A very limited number of ship station locations were selected for comparison to OCS radiometric chlorophyll analysis. These locations shown in dots were selected primarily on the basis that they were situated at a near nadir position in relation to one of the U2/OCS flight tracks. The near nadir position provided a minimal optical path from the ocean to the OCS and presumably allowed the atmospheric contribution to the detected signal to be estimated most accurately. In addition, the measurements at these positions were taken as near in time as possible to the time of the aircraft overpasses. Determination of the ship station locations relative to the OCS flight tracks was greatly aided during the 1979 and 1981 flights by direct sighting of the ship in the OCS data and photographs taken from the aircraft. During the 1980 exercise, the measurements from the surface ship were taken 10 hours after the U2 overpass. However, the measurements were considered valid for analysis because the elapsed time was well within the time scale of change observed during this experiment. A listing of the measurement points, along with the time of measurement and observed data is provided in Table 1. The chlorophyll concentrations at each ship station were determined at several depths from the discrete

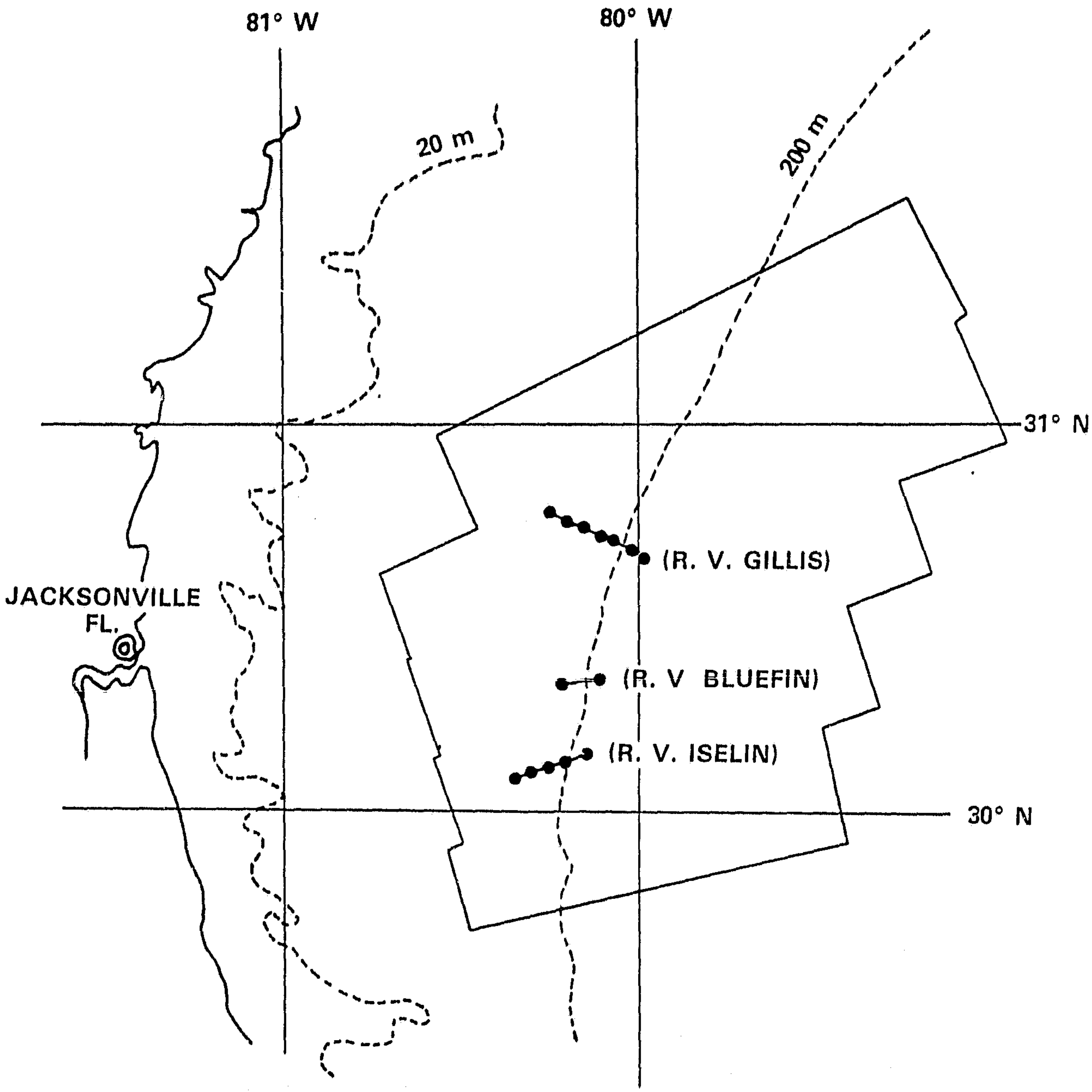

Figure 2. The areal coverage of U2/OCS in 1980 and station locations in 79-81 are shown in dotted and solid lines.

samples which were collected. The samples were analyzed for chlorophyll-a and phaeopigment as described by Yentsch and Menzel[4] and as later modified by Strickland and Parsons[5]. The ship data show that a large subsurface chlorophyll peak at 15 to 50 meters is usually present, but the top 0 to 15 m is approximately uniform. This subsurface chlorophyll peak is not expected to influence the

Table 1. Shipborne Chlorophyll Data and U2/OCS Radiance Data.

Ship Station	Time Stop (D:hr:min)	Chlorophyll (mg/m^3)	Flt. No.	OCS Flt. (D:hr:min)	SZA	Radiance Measured*			
						431nm	472nm	548nm	778nm
R.V. Gillis 210	4:28:79:16:00	0.28	62	4:28:79:16:13	56°	4.44	4.10	2.08	0.48
R.V. Gillis 211	4:28:79:16:40	2.16	62	4:28:79:16:14	56°	4.14	3.91	2.17	0.48
R.V. Gillis 212	4:28:79:17:20	4.64	62	4:28:79:16:14	56°	4.17	3.85	2.17	0.49
R.V. Gillis 213	4:28:79:17:50	5.45	62	4:28:79:16:15	56°	4.03	3.78	2.13	0.47
R.V. Gillis 214	4:28:79:18:00	3.47	62	4:28:79:16:16	56°	4.08	3.76	2.09	0.47
R.V. Gillis 215	4:28:79:19:00	1.45	62	4:28:79:16:17	56°	4.18	3.85	2.09	0.48
R.V. Gillis 216	4:28:79:20:00	1.50	62	4:28:79:16:17	56°	4.10	3.89	2.09	0.48
R.V. Iselin 118	4:16:80:02:00	0.5	63	4:16:80:15:30	48°	5.67	5.19	2.62	0.58
R.V. Iselin 118	4:16:80:02:20.	1.8	63	4:16:80:15:31	48°	5.66	4.93	2.69	0.59
R.V. Iselin 119	4:16:80:02:30	0.6	63	4:16:80:15:32	48°	5.91	5.15	2.71	0.72
R.V. Iselin 119	4:16:80:02:50	2.2	63	4:16:80:15:34	48°	5.58	4.90	2.77	0.56
R.V. Iselin 119	4:16:80:03:10	2.2	63	4:16:80:15:38	48°	5.54	4.93	2.74	0.69
R.V. Bluefin 218	4:23:81:12:50	0.18	65	4:23:81:15:20	50°	5.88	4.85	2.44	0.62
R.V. Bluefin 219	4:23:81:14:30	0.42	65	4:23:81:15:21	50°	5.68	4.79	2.48	0.64

*mw/cm^2-μ-sr

radiometric readings of a high altitude remote sensor. Therefore only the immediate surface chlorophyll values were considered relevant and they are listed in Table 1. The radiance values given in the columns 7 to 11 of Table 1 are from the OCS measurements. Each radiance value is an averaged value of a group of 25 contiguous pixels which have been determined to be surrounding the respective ship station. The characteristics and performance specifications of the U2/OCS instrument were given in the previous report[3]. We made only negligible modifications or changes to this instrument during the course of the three year experimental period. In designing the locations and patterns of flight tracks in the OCS overflight series, we gave specific attention to two factors which can severely affect the value of measured radiance and subsequently adversely influence the reliability of the generalities derived from the data. These complicating factors were sun glint and hydrosol scattering. To minimize the effects of these factors, we placed the following restrictions on the OCS operations:

a. Avoidance of direct sunlight reflected from the ocean surface. The scanner was only operated in the late afternoon between 3 to 5 P.M. when the sun is above the horizon by 30 to 50 degrees. The aircraft alway flew nearly directly toward or away from the sun when the scanner was switched on. This particular maneuver helped in reducing the effects of the sun glint off the sea surface onto the sensor.

b. Avoidance of the effects of continental sediment. This particular region of the SAB was chosen as the test site for the reasons that the targeted phytoplankton blooms are characteristically free of any continental sediments. The blooms are associated with intrusions of North Atlantic waters of the deep layer onto the shelf. Any significant radiative transfer processes taking place under these conditions would be by and large limited to the absorptional phenomena by the chlorophyll pigment in the blue region. In this context, the area water will perhaps fall within the category of Morel's "Case 1 water" or the "Desert water" against the turbid coastal water[6]. Accordingly the analysis scheme being discussed in this article would be limited to oceanic conditions with this sort of hydrospheric homogeneity and clarity.

ANALYSIS METHOD

A number of investigators have already demonstrated the feasibility of ocean color measurement in the determination of the relative chlorophyll richness in the ocean[7,8]. A more difficult extension of their techniques is in the quantitative determination of the chlorophyll. Application of quantitative chlorophyll algorithms from high altitude aircraft or space is an especially difficult problem due to the influence of atmospheric radiance. Atmospheric optical properties can vary substantially in time and space. A properly designed atmospheric model will yield values for the separate radiance components of an ocean-atmosphere system. Then since the concentration of chlorophyll affects the sub-surface oceanic reflectivity, elimination of the contributions from all above surface sources from the total upwelling radiance will yield a value which can predict the pigment load.

Over the years, many investigators have developed methods to estimate the radiative fluxes which one would expect to measure in the atmosphere. Most of these methods are based on the theories of Rayleigh and Mie concerning the scattering of light wave energy by atmospheric molecular and particulate matter. The theories are incorporated into schemes which permit the investigator to adjust the physical characteristics of the atmosphere and its lower boundary and then calculate the theoretical radiative flux and radiance at arbitrary levels from the earth's surface up to the top of the atmosphere. An example of a complex method is one developed by Plass et al[9] which uses a Monte Carlo technique which follows the progress of individual photons through the atmosphere. This method allows much flexibility in the description of the physical make up of the atmosphere, and its boundaries. A second method solves the differential equation of radiative transfer after first determining the volumetric scattering properties of the atmospheric constituents[10]. In this study, we opted to employ such a method, specifically one which was developed by J. V. Dave[11] to aid our calculation of upwelling ocean radiances. The Dave method exists in a large set of computer programs commonly referred to a "Dave Code." The final output from these programs provide the following results which are pertinent to our studies:

a. Upwelling radiance at several levels of the atmosphere, including one very near the altitude of the U2/OCS flights. These calculations are produced for scan angles from 0 to 90°, for specified azimuth angles and for a specified set of surface albedos.

b. Upwelling flux and downwelling radiance at the lower boundary of the atmosphere.

The use of these programs requires that certain properties of the airborne particulate matter are assumed to be known. These assumptions are that refractive index and the particulate size distribution and vertical distribution are known. We also assume that the final calculations are not significantly sensitive to reasonable deviations of these assumptions from actuality.

Another important assumption is that the lower boundary acts as an unpolarizing Lambertian reflector. In the case of the ocean, this Lambertian assumption is applied to the upwelling radiance transmitted through the water's surface while the specular reflection of downwelling sky light is assumed to be small for the useful range of scan angles. Also, the reflection of direct sunlight from the ocean surface is ignored because we assume that the conditions of relatively low sun elevation and scanner viewing geometry effectively render this component negligible.

INFORMATION ON ATMOSPHERIC AEROSOLS

The use of the Dave code results to derive upwelling ocean radiance depend substantially on the fact that the OCS has a detecting channel in the near infrared spectral region at 778 nm (channel 10). Ocean water is highly absorbent of light radiation at that wavelength and, for our purpose, the subsurface albedo is considered to be zero or nearly zero. This assumption allows us to regard the total signal detected by this near infrared channel to be produced by atmospheric scattering, which is the result of Rayleigh and Mie processes. The useful information which is contained in this signal is the amount of particulate matter in the atmosphere; that is, the aerosol optical depth which is contributing to the scattering signal. Since the albedo of the surface boundary and the Rayleigh optical depth are known, the total signal is considered as a function of the aerosol optical depth and aerosol size distribution. Radiative transfer theory can be used to find the relationship between aerosol optical depth and detected upwelling radiance. By using the radiance detected by the OCS, the aerosol optical depth below the instrument can be calculated from the theoretical relationship. Once the aerosol optical depth in the atmosphere is established, it can be used to determine the reflectance of the ocean-atmosphere system at other visible wavelengths. Under our set of assumptions, the radiance detected by each OCS visible channel is a function of aerosol optical depth, aerosol size distribution and ocean albedo. Similar to what is done with the near infrared radiation. Radiative transfer calculations can be used to find that relationship. Then, by using the measured OCS radiance at the visible wavelengths along with the estimated aerosol optical depth and size distribution and the ocean albedo can be calculated from the relationship. The radiative transfer calculations also yield the upward ocean flux as a function of ocean albedo. Thus, the ocean surface flux can be calculated, and by using the assumption of a Lambertian reflector, the surface radiance in any direction can be computed. As mentioned earlier, the application of the ocean radiance algorithm requires that a specific model be assigned to the size distribution of the aerosol particles assumed to be in the atmosphere. We assumed that the aerosol size distribution follows the Junge distribution, given by

$$dn/dr = c\, r^{-(\nu^* + 1)} \tag{1}$$

where dn is the number of particles with radius between r and r+dr and ν^* and c are constants. In order to obtain a representative value of aerosol optical depth, τ, solar transmissometer measurements were taken from the R.V. Bluefin during the GABEX-81. On the afternoon of April 23, 1981, which was the period of a U2/OCS overflight, the relative irradiance of the directly transmitted sunlight was measured at 8 discrete wavelengths between 440 and 870 nm. From this sequence of the measurements obtained in the SAB (30°N, 80°W), we obtained the aerosol optical depth of the atmosphere after correcting the total optical depth measurements for Rayleigh scattering and ozone absorption using the method of King and Byrne (See Fig. 3)[12]. Having determined the spectral aerosol optical depth, it is possible to derive the aerosol size distribution using constrained linear inversion methods[13]. These results which assume that the refractive index of the aerosol particle is 1.45 - 0.0 i, are presented in Fig. 4. In addition to the inverted size distribution a Junge distribution with $\nu^* = 3.0$ is illustrated. Since the inverted size distribution has a slope nearly identical to the Junge distribution for the majority of the optically important radii, the radiance computed from both of these models is expected to be similar. For this reason we assumed a Junge distribution with $\nu^* = 3.0$ in all radiative transfer computations presented below.

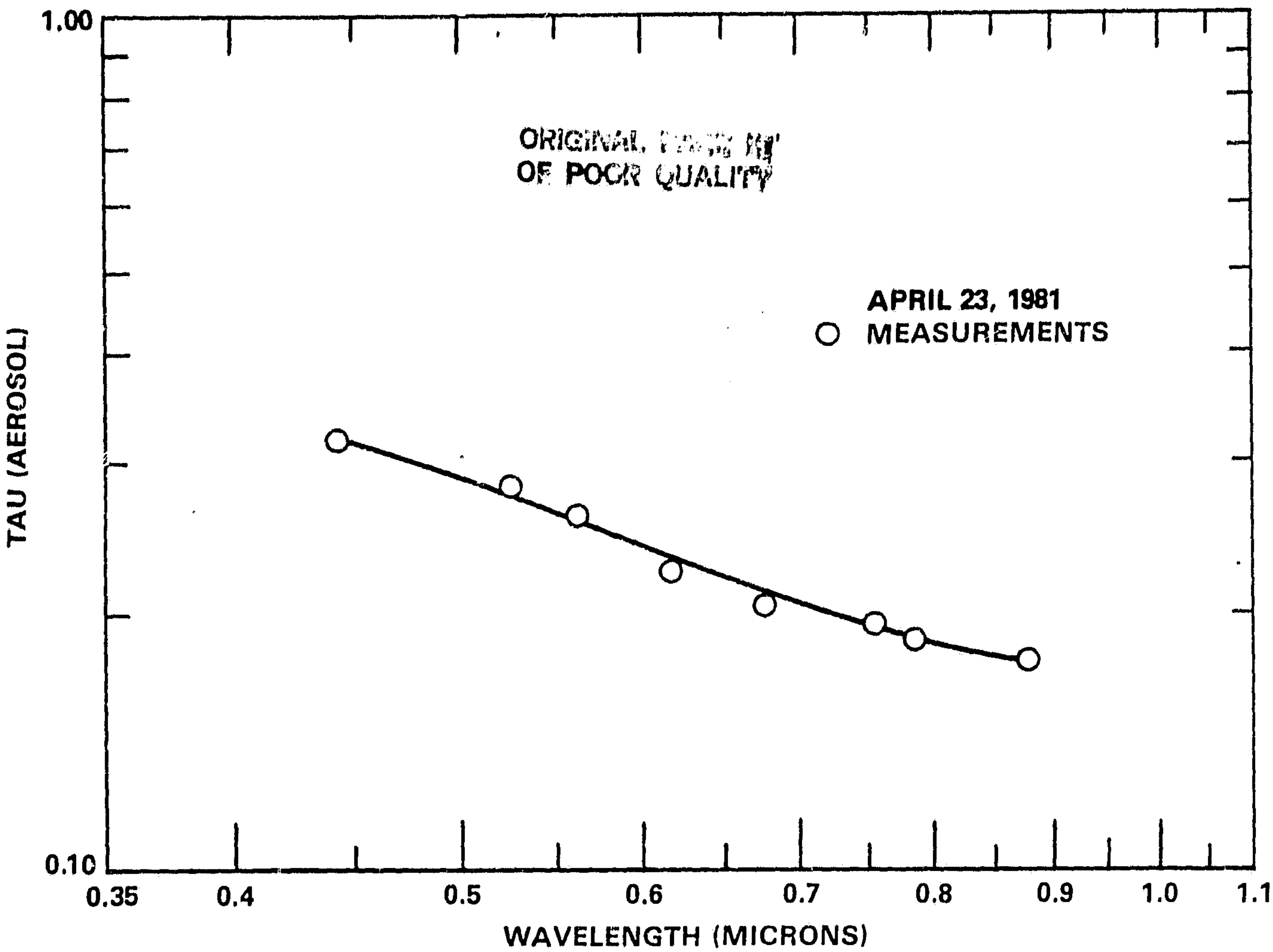

Figure 3. Aerosol optical depth as a function of wavelength was taken at the SAB (30° N, 80° W) on April 23, 1981. The smooth curve represents the regression fit to the data using the inverted size distribution presented in Fig. 4.

COMPUTER PROCESSING ALGORITHMS

The ocean radiance algorithm, described above, was programmed for operation on a large computer so that entire flight segments could be analyzed. The summary of the logical steps taken within the program is given below. The final product of the program is an estimate of the upwelling ocean radiance for each data point in an OCS flight segment for a given wavelength. The major steps are:

Step 1. Determine specific solar ephemeris for the OCS flight segment:

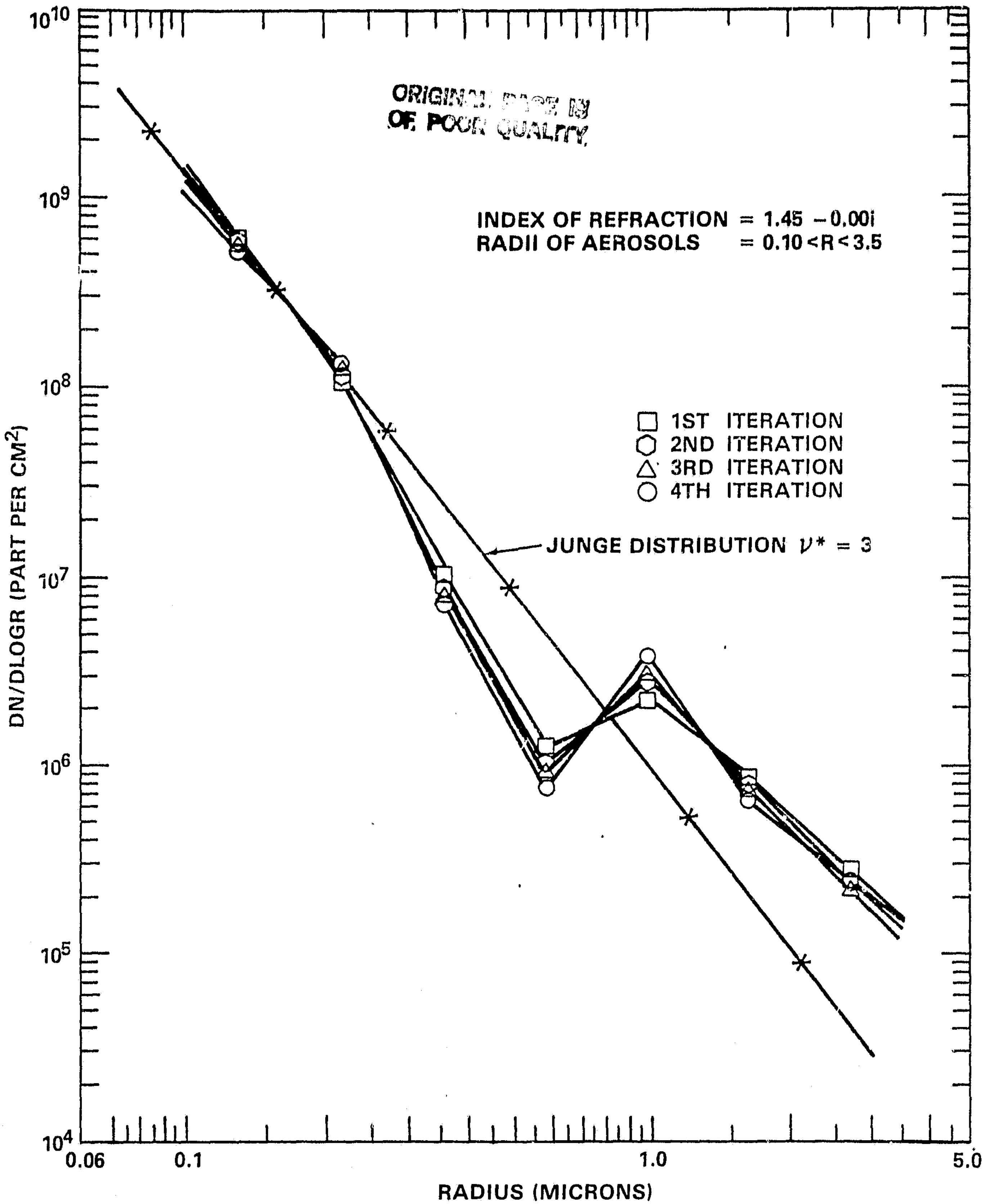

Figure 4. Aerosol size distribution obtained by inversion of the spectral optical depth measurements presented in Fig. 3. The straight line represents a Junge size distribution with $\nu^* = 3.0$ which was used in the atmospheric model calculations.

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a. solar zenith angle and

b. relative azimuth angle of the sun in relationship to an OCS scanline.

Step 2. Calculate theoretical relationship between detected upwelling radiance in near IR channel and concentration of aerosols; using the proper values of solar parameters determined in step 1, run the radiative transfer models (Dave Code) for at least two different amounts of atmospheric aerosol concentration. Then store the results of these calculations on magnetic tape for the entire range of OCS scan angles.

Step 3. Calculate theoretical relationship between detected upwelling radiance, aerosol amount, ocean reflectivity, ocean upwelling flux:

a. For a specific wavelength of visible light, run the Dave Code for at least two concentrations of aerosol and the range of ocean reflectivities which are expected for the wavelength.

b. Store the results of these calculations on magnetic tape for the entire range of OCS scan angles.

Step 4. The relationships among the observed upwelling radiance, aerosol content, and the ocean reflectivity are parameterized by performing a linear regression on the results of step 2 and 3:

a. corresponding to step two, a linear regression is done for each scan angle corresponding to the angular position from nadir of each of the 265 data points in the OCS scan. The form of this regression is

$$N_i = a_i I_i + b_i \tag{2}$$

where N_i is the columnar aerosol load for data point i, I_i is the upwelling OCS radiance of the IR channel, a_i, b_i are the constants determined from the theoretical modelling results in step 2. Use of this regression is equivalent to linear interpolation. This regression is performed using surface reflectivities of between zero and one percent. A non-zero reflectivity is used as an adjustment for the fact that the diffuse sky Fresnel reflection is not zero, but it is not explicitly calculated.

b. A multiple linear regression is performed from the calculations of step 3. The form of the regression equation is

$$\omega_{ij} = \alpha_{ij} I_{ij} + \beta_{ij} N_i + \gamma_{ij} \tag{3}$$

where ω_{ij} is the ocean albedo for scan position i and wavelength j, I_{ij} is the detected upwelling radiance, point i, wavelength j, N_i is the columnar aerosol load for point i, α_{ij}, β_{ij}, γ_{ij} are the constants determined from the multiple regression. Use of this equation is equivalent to bilinear interpolation.

Step 5. Calculation of the aerosol concentration for a specific OCS data point:

a. Obtain the observed OCS near IR radiance for a specific data point.

b. Use equation (2) to determine the aerosol concentration at the point.

Step 6. Calculation of the upwelling ocean albedo and radiance for a particular wavelength:

a. Obtain the observed OCS radiance for wavelength j at the point used in step 5.

b. Use equation 3 to calculate the ocean reflectivity at the point for the specified wavelength.

c. Use bilinear interpolation to obtain upwelling ocean radiance at the data point from the values of aerosol concentration and reflectivity already calculated. An illustration of the essential characteristics of the calculation are given in Figure 5. The linear regressions referred to above derived coefficients which essentially determine the functional planes which are theoretically calculated from the Dave Code and depict the relationship among the albedo, aerosol concentration, and total measured radiance for each wavelength. A numerical example is pictured on the graph. A total measured radiance at 778 nm of 0.47 mw/cm^2-μ-sr yields an aerosol concentration of 1.35 x 10^8 particles/cm^2. This concentration along with a measured radiance of 4.10 mw/cm^2-μ-sr at 472 nm intersects the theoretical plane at an albedo of 3.7%. Using the derived value of albedo and aerosol concentration, the upwelling ocean radiative flux

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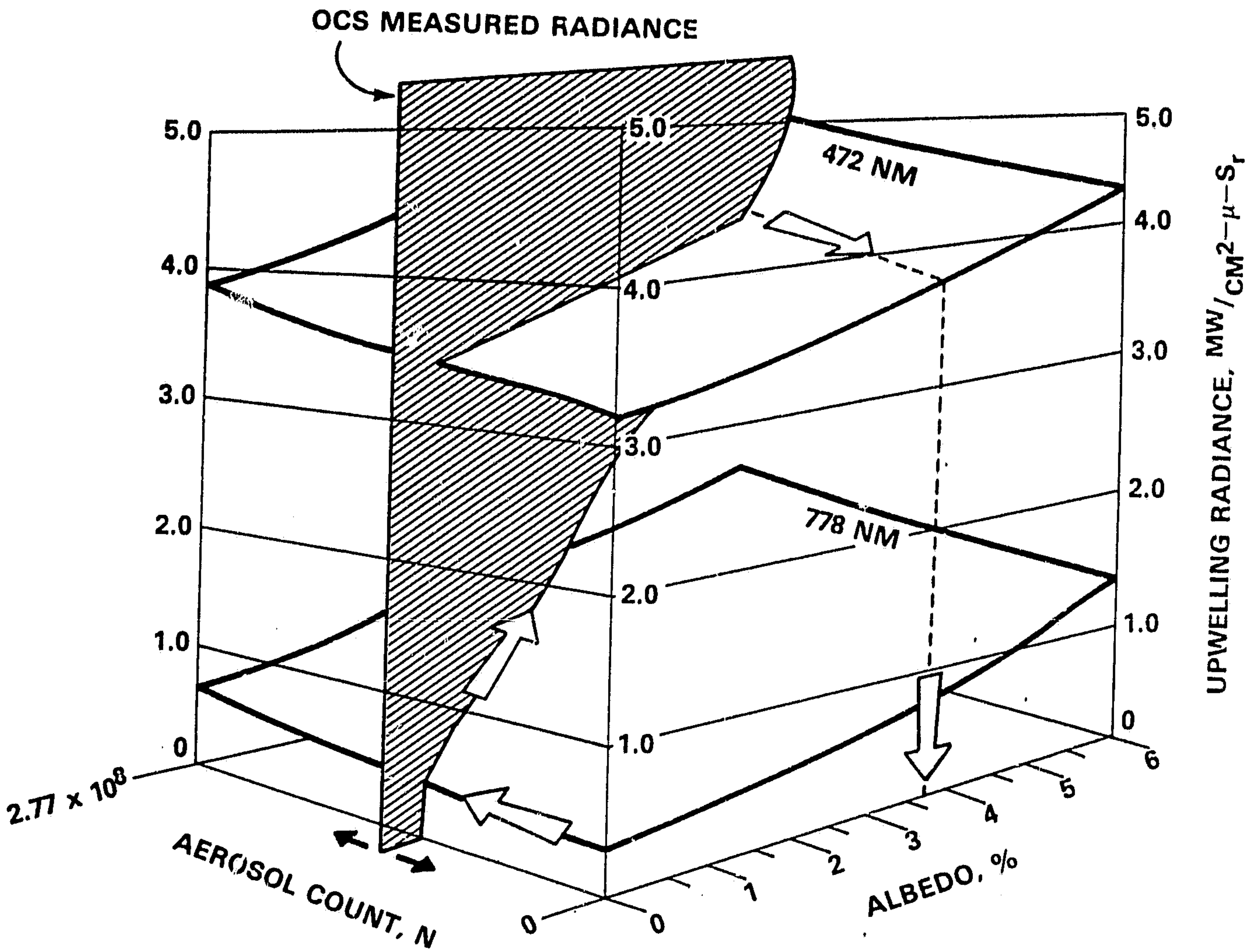

Figure 5. Upwelling radiances at 472 nm and 782 nm are shown as a function of aerosol and lower boundary albedo. The modelled curves are for SZA = 56° and a nadir-look sensor at 19.8 km altitude.

can be interpolated from the graph shown in Fig. 5. In Table 2, a breakdown of various radiational components for the OCS data taken from three SAB stations are given. The data comprise three different sets of solar zenith angle and aerosol content.

VALIDITY OF ANALYSIS METHODS

A valid ocean color derived chlorophyll content analysis method must be able to apportion the total measured atmospheric radiance in a manner which gives the correct values to the subsurface

Table 2. A Breakdown of Various Radiational Components of Three SAB Stations.

λ (nm)	Meas. Rad*	Albedo (%)	Dn Flux†			Upwell Rad			Atm Rad	Chl. Con. (mg/m^3)	Ratio (R_{14})
			Solar	Diff	Total	Fresnel	Water	Total			
431	4.03	1.49	45	23	68	0.01	0.31	0.32	3.71	5.45	0.75
472	3.78	2.68	66	24	90	0.01	0.76	0.77	3.01		
548	2.12	1.55	68	18	86	0.006	0.42	0.42	1.70		
778	0.47	0	52	7	59	0	0	0	0.46		
Gillis Station 218				SZA = 56°			$N = 1.35 \times 10^8$				
431	5.66	5.5	42	40	82	0.01	1.44	1.45	4.21	1.8	1.69
472	4.93	5.3	65	39	104	0.01	1.74	1.75	3.18		
548	2.69	2.64	70	32	102	0.01	0.85	0.86	1.83		
778	0.66	0	54	15	69	0	0	0	0.65		
Iselin Station 118				SZA = 48°			$N = 2.7 \times 10^8$				
431	5.88	6.9	45	36	81	0.01	1.77	1.78	4.1	0.18	2.53
472	4.85	5.5	70	35	105	0.01	1.83	1.84	3.01		
548	2.44	2.3	70	26	96	0.05	0.70	0.70	1.74		
778	0.62	0	56	15	71	0	0	0	0.61		
Bluefin Station 218				SZA = 50°			$N = 2.6 \times 10^8$				

*Radiance: mw/cm^2-μ-sr

†Flux: mw/cm^2-μ

radiance component, which is of prime importance, and to the above surface and surface radiance components which are only indirectly important. The analysis should produce correct values regardless of time or place within the constraints imposed by assumptions of the analysis. Since the concentration of chlorophyll affects the subsurface oceanic reflectivity, elimination of the contributions from all above surface sources from the total upwelling radiance yield a value which can predict the pigment load.

The validity of a given ocean atmospheric computation method is inevitably judged by how well the resultant subsurface radiance relates to chlorophyll content. Unfortunately the common chlorophyll algorithms in use today are based on one-dimensional linear regressions which smooth over or ignore variabilities common in physical ocean characteristics. Precision and repeatability in chlorophyll relation greatly depends on optimized data collection strategy.

In our SAB study, the optical properties of the sea water being observed are very likely only influenced by the chlorophyll pigment absorption. Therefore the expected effect on the color of the ocean of increasing the concentration is a decrease in the intensity of blue spectral channels. An assortment of chlorophyll pigments (chlorophyll-a,b,c and phaeopigment) contribute to absorption in the relatively broad "blue band".

The OCS was designed to provide three strategically placed optical channels at 431 nm, 472 nm, and 506 nm (channels 1, 2, and 3) to monitor this absorptivity. In addition, a non-absorbing green channel at 548 nm (channel 4) was available to provide information on hydrosol scattering. Among short wavelength channels available for chlorophyll monitoring, the overall performance of the 472 nm was superior to that of any other channels for several reasons. The channel has a large signal-to-noise ratio and the chlorophyll absorption in this region is still significantly large. In addition the Rayleigh scattering effects and the uncertainty of the solar spectral constants of this channel are less severe than that of the 431 nm channel. For these reasons, the ratioing of the differences at 472 nm and 548 nm channel over the sum of the two radiances had been used in our previous OCS studies to express the chlorophyll concentration.

$$R_{24} = I^{w}(472\text{ nm}) - I^{w}(548\text{ nm}) \,/\, I^{w}(472\text{ nm}) + I^{w}(548\text{ nm}) \tag{4}$$

where I_i^w denotes the water leaving radiance at wavelength i nm. A plot of the measured chlorophyll concentration vs. the derived ratio of the two channels for the fourteen data points of Table 1 is shown in figure 6. A least square fit resulted a regression line with the following empirical relationship

$$C = 275\ \mathrm{Exp}(-15\ R_{24}) \tag{5}$$

The square of the linear correlation coefficients for the above data set in log (c) vs. Ratio_{24} was 0.85.

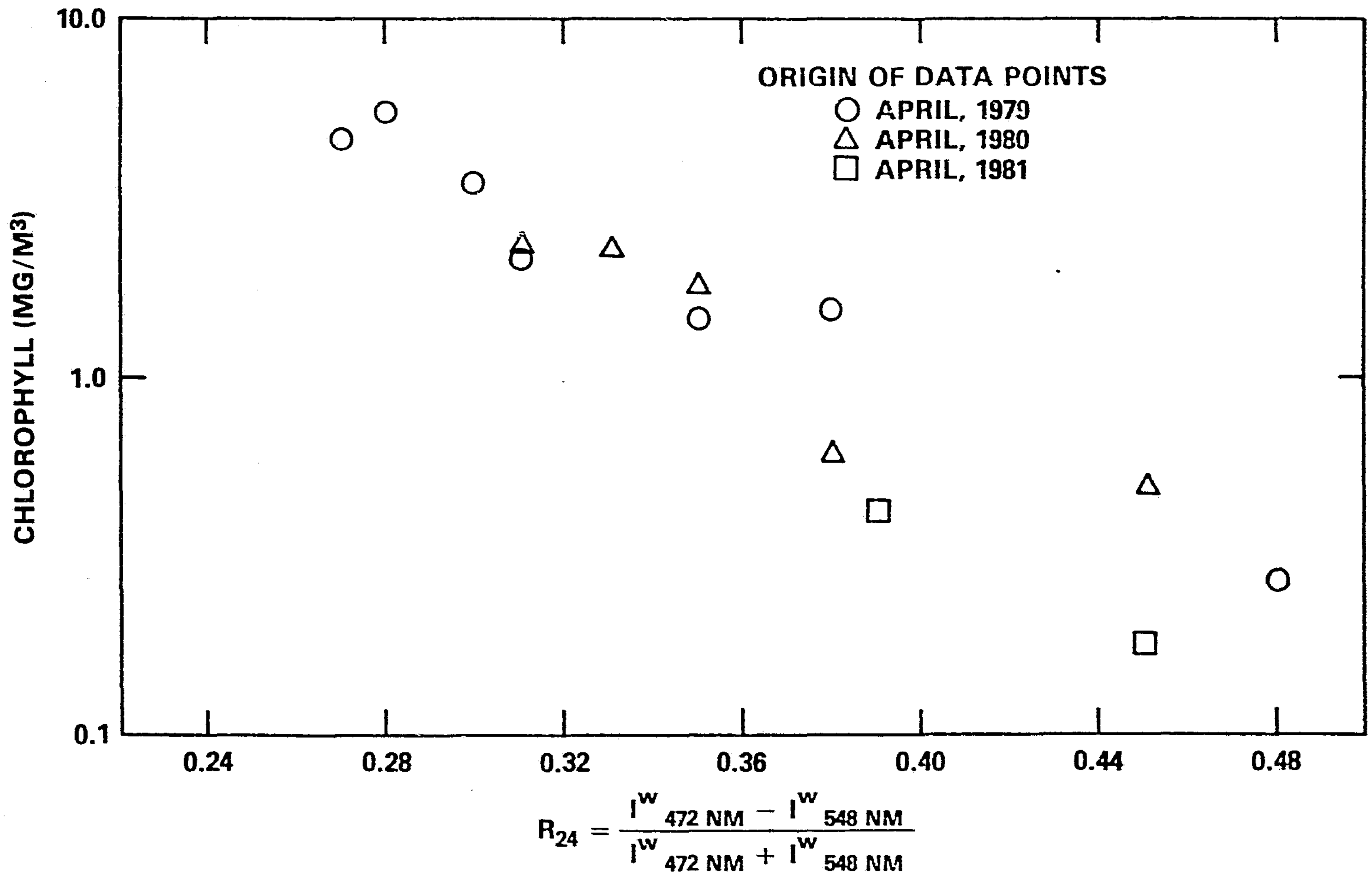

Figure 6. Relationships between the measured chlorophyll concentration C and the derived ratio products R_{24}. The correlation coefficient for the 14 points was 0.85.

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The Coastal Zone Color Scanner (CZCS) on Nimbus-7 satellite which was launched August 1978 is the only satellite sensor dedicated to oceanic studies still in operation. The scanner has three optical channels, 443 nm, 520 nm, and 550 nm, to retrieve chlorophyll concentration. A number of CZCS data users have compared the satellite data with chlorophyll data gathered concurrently by ships[14,15,16,17]. The CZCS chlorophyll analysis algorithms are based on the relationships between chlorophyll concentration and blue light absorptivity according to the following power curve relationship

$$C = a\,(R_{14})^{b} \tag{6}$$

where R_{14} denotes the ratio of the water radiance at 443 nm to that at 550 nm channel. The OCS combination of 431 nm and 548 nm is the closest to the CZCS combination of 443 nm and 550 nm. For the purpose of comparative study, the OCS radiances of the 431 nm and 548 nm channels given in Table 1 were processed and empirically related to the chlorophyll content according to equation 6. A plot of the resultant curve presented on a log (Log scale is shown in Figure 7.) The curve is presented so as to show the statistical uncertainty resulting from the scatter of data points about the regression line. The center line represents the curve derived by a least square fit of the 14 data points. The bounding lines represent a standardized range of uncertainty in the estimated coefficients and are based on the standard error of regression for coefficients a and b. It is thus reasonable to expect the true relationship between chlorophyll and R_{14} to fall within the hatched area of graph, at least for the physical conditions of the SAB project. The OCS center line regression coefficients a and b are given in Table 3 along with the coefficients which have been reported by others. In addition to the above empirical studies, several theoretical studies[19,20] which relate ocean radiance to chlorophyll concentration have been published. For instance, Plass et al synthesized a series of ocean radiance spectra based on a theoretical approach using a Monte-Carlo model. From these studies, one can gain certain insight on the chlorophyll influence in general. As a point of interest,

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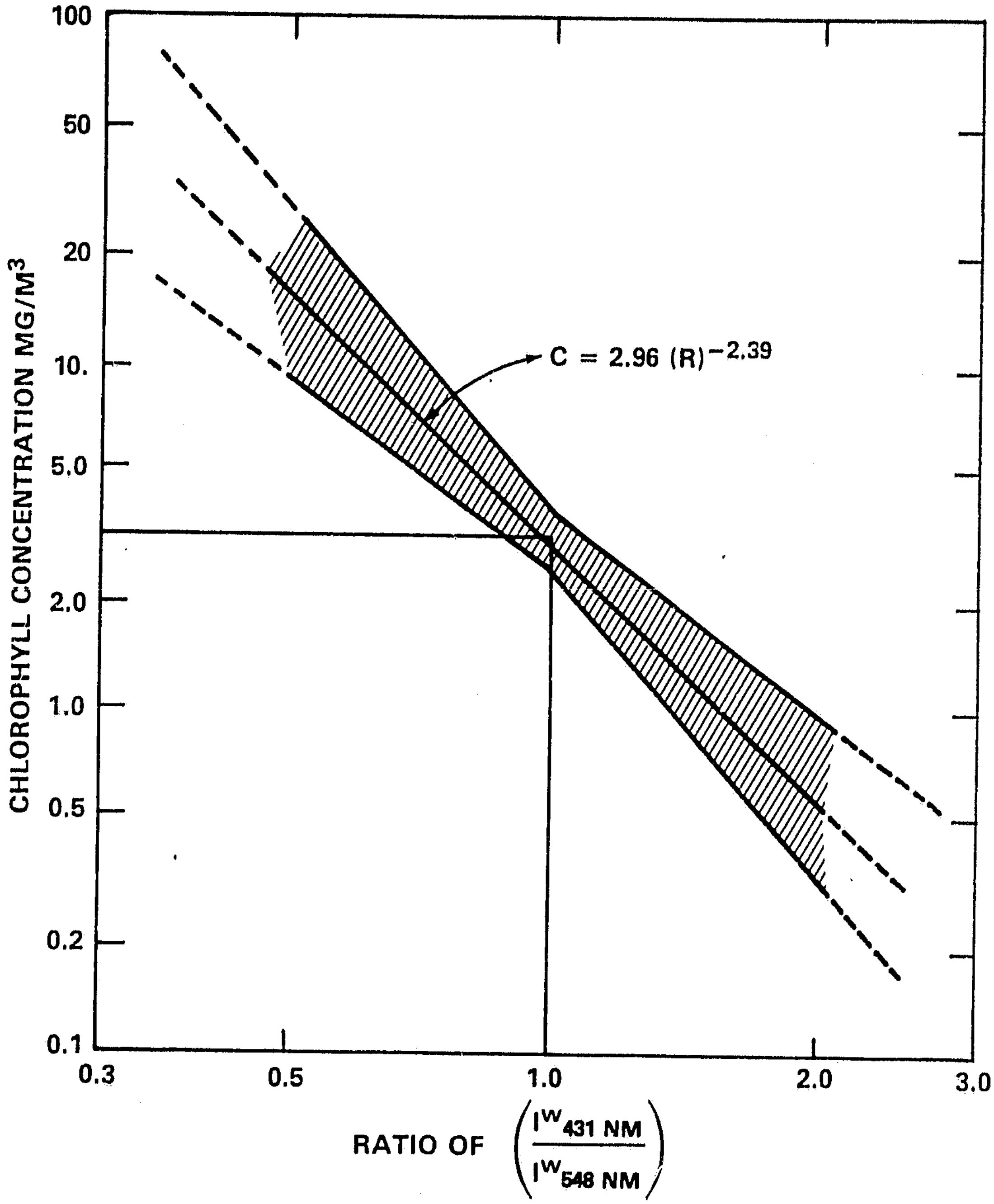

Figure 7. Relationship between Log C and Log (R_{14}). The hatched area represents a range of uncertainty in the estimated coefficient a and b based on the standard error of regression.

Table 3. Chlorophyll Correlation Coefficients by Various Investigators

Investigators	Data Base, Method, Study Years & Refs.	Regression Coefficients a	Regression Coefficients b
G. Clarke, et al	Low altitude aircraft, 1967-68(7)	5.4	-2.8*
D. Clark, et al	Shipboard subsurface measurements, 1977(18)	0.5	-1.3
Gordon, et al	CZCS satellite imagery 1978,(14)	0.5	-1.3
Gordon, et al	CZCS imagery for 'Case-1' water, 1983,(15)	1.3	-1.71
Morel	Shipboard subsurface measurements, 1977(6)	2.0	-1.9
Smith and Baker	CZCS satellite imagery 1978-1980,(17)	1.23	-2.6
This Study	High altitude Aircraft, 1979-81	3.0	-2.4

*Estimated by the authors

values of chlorophyll content and radiance were extracted from their published graphs. When chlorophyll was related to R_{14} in a manner similar to that in Table 3, the resulting coefficients were found to be a = 1.34 and b = -1.5 for all the non-zero chlorophyll cases of open ocean and hydrosol and Gelbestoeffe laden waters. However, the listings in Table 3 are limited to those field data studies to evaluate each analysis method.

DISCUSSION

The dissimilarities among those a and b parameters listed in Table 3 are discouraging. For instance, one of the largest discrepancies in a and b values occur between the earlier work of Gordon and Clark and that of ours. The difference between the two is significantly large and this fact has been the source of controversies[21,22]. In order to demonstrate the practical meaning of the difference between the parameters in Figures 8a and b relative height of water radiances at 443 nm and 550 nm for the Gordon and Clark's case, a = 0.5 and b = -1.3, and by this study, a = 3.0 and b = -2.4 are plotted. The figures indicate that the influence of chloro-

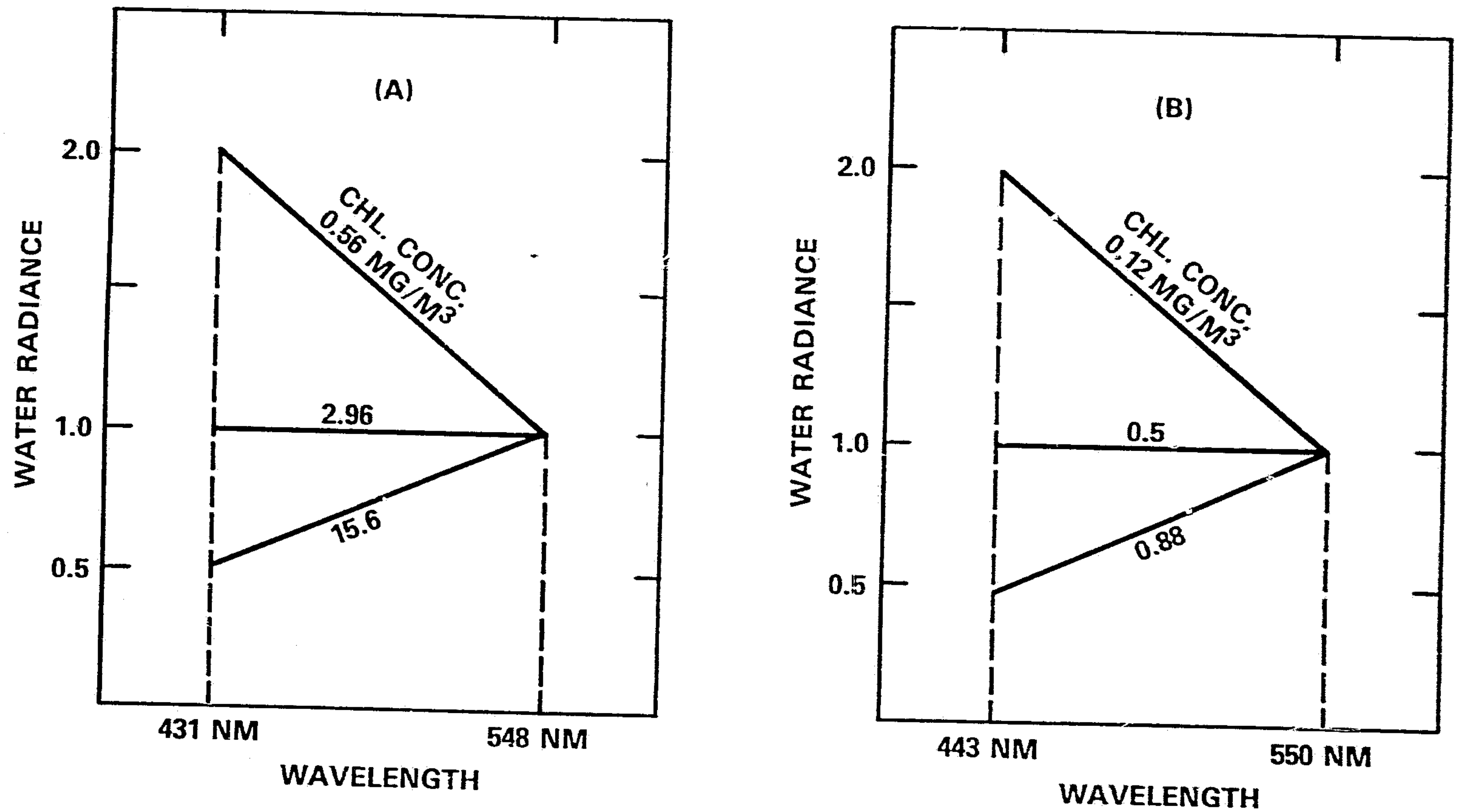

Figure 8. Chlorophyll concentrations necessary to attain the above spectral curve slopes: a) for $C = 2.96(R)^{-2.4}$ from this study and b) for $C = 0.5(R)^{-1.3}$ from Gordon and D. Clark (CZCS).

phyll pigment in the water is such that the negative slope of a monotonically declining spectrum curve of the open ocean case will change sign when the pigment concentration exceeds a certain value. According to Gordon and Clark's analysis when the chlorophyll load reaches 0.5 mg/M^3, the water radiance at 440 nm and 550 nm will become equal. At approximately 0.9 mg/M^3, the water radiance at 440 nm channel will be about a half of that at the 550 nm. The OCS results display much less dependence of the ratio on chlorophyll change. The difference between the CZCS and OCS results are very large. Apart from the discrepancies which can be attributed to the wavelength difference in 431 nm, or to using ratios in terms of reflectances rather than radiances, there are several reasons which may account for this wide range of variabilities in chlorophyll relations. To illustrate this we examine the case of Morel's data. Here, the empirical relationships were totally derived from subsurface measurement statistics, which had been carried out using submersible spectrometers near the surface. Significantly, Morel was first to separate 12 spectral curves obtained in Antartic Ocean cruise in 1978 from 10 curves obtained in Mediterranean Sea in turbid waters near Marseille. From these data, a classification was established and two extreme cases were identified and referred to as "Case 1" and "Case 2". "Case 1" corresponds to waters for which the optical properties are to a large extent limited to the open ocean case as in the SAB. Clark and Gordon also conducted their measurements from shipboard as a part of the CZCS validation activities in 1977. Measurements of the upwelling spectro-radiance were made with a 2-degree field-of-view submersible spectrometer covering a spectral range from 400 nm to 700 nm. A regression analysis of these ship data relating chlorophyll concentration, C, to the radiance ratio, R_{14}, yielded the values for log (a) and b are -0.297 and -1.269, respectively. They also reported that this empirical relationship was found to coincide with derived CZCS radiance data after removing the atmospheric effects as proposed by Gordon[23]. But Gordon and Clark's ship data include those data which had been taken from the Mississippi River Mouth along with those data from the Sargasso Sea. They did not separate the open ocean case from the turbid waters. We feel that this fact is so important that it actually renders irrelevant comparison between their coefficients and ours. However, in the recent work of Gordon et al,[15] they separate open ocean water, "Case 1," from the situations for chlorophyll concentration is greater than 1.5 mg/M^3 which is a case they consider is a mixture of "Case 1" and "Case 2." The derived chlorophyll coefficients for "Case 1" are still considerably off from that of ours.

In terms of similarity the Clarke's et al[7] measurements of water conditions are very similar to our SAB study. Clarke et al were the first to provide scientific evidence that it is possible to use the color of the ocean to estimate the chlorophyll concentration in surface water. In the summers of 1967 and 1968, they compiled over 3,000 ocean spectra from 300 and 3,000 meter altitude together with ground truth. They measured before and after each series of flights, the spectrum of the incident light from the Sun and sky by placing Eastman Kodak "Grey Card" with non-selective reflectivity of 18 percent in front of the spectrometer. In figure 9, Clarke's et al spectra of backscattered light measured from an aircraft at an altitude of 305 m are presented. The vertical lines at 440 nm and 550 nm have been added by the authors to indicate the reflectivities at those two wavelengths. The estimation of albedos as we do with the Dave Code and the flight track which cross the Gulf Stream onto the shore slope are very similar to our SAB study. Regression coefficients a and b based on C, D and E slopes of Figure 9 are 5.4 and -2.77. There are other reasons which might be the causes of the discrepancies among the data listed in Table 3. One possible cause is that the removal of intervening atmospheric effects is not done correctly. However, the authors are inclined to think that the radiative transfer processes of the atmosphere can be reliably calculated and that the various computation methods are adequately valid. The difference between the CZCS and our OCS atmospheric algorithms is that the CZCS method is based on single scattering; whereas the OCS method properly accounts for multiple scattering. However, errors may still arise in our radiative transfer calculations as a result of neglecting the effects of polarization in the calculations. Both the effects of multiple scattering polarization are important for cloud free atmosphere at visible wavelengths.

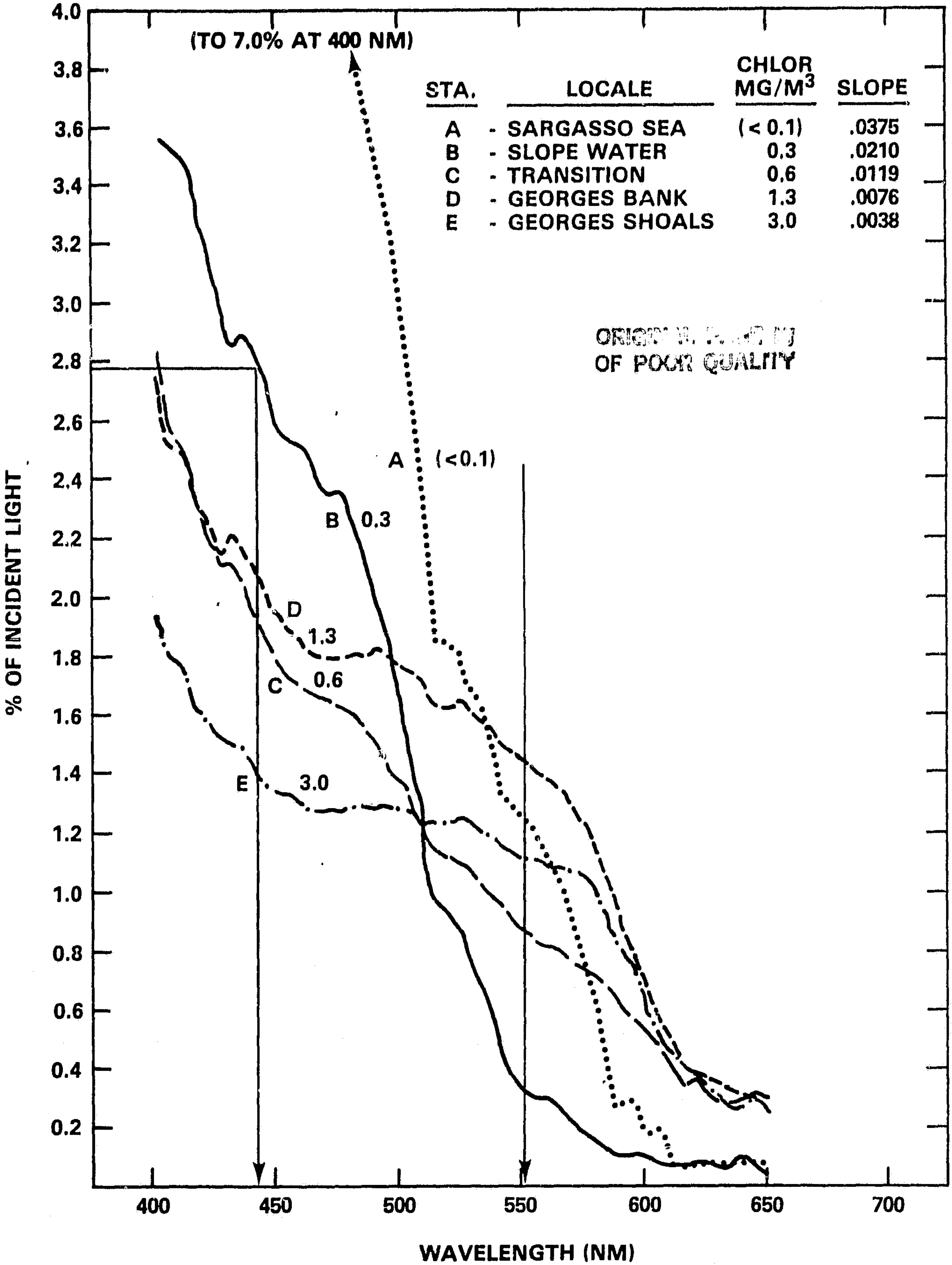

Figure 9. Spectra of upwelling radiances measured from an aircraft altitude of 305 m by G. Clark et al in 1968. Estimated regression coefficients a and b for curves C, D, and E are 5.4 and - 2.77.

Recently Smith and Baker[17] reported the results of CZCS imagery analysis in which satellite data were compared with data gathered by ships. Even though the Smith and Baker used modified algorithms originally developed by Gordon, the a and b parameters they obtained are considerably different from the Gordon and Clark's values. Smith et al attribute this dissimilarity to the problem of optimizing the ship and satellite data to extract the most accurate chlorophyll values from a CZCS image.

The next logical question to be raised will likely pertain to the accuracy of the radiometric values being cited by each investigator. The outcome of the results can be seriously influenced by even a small error in radiometric calibration, as each investigative team will rely on the data sets of their particular instrument. The OCS instrument is calibrated by using a 1.83 meter integration sphere immediately before and after each flight to assure the radiometric accuracy of the instrument. The integration sphere is calibrated against a National Bureau of Standard's standard lamp and the sphere is maintained with a 2% fluctuation limit to the sphere reading and a 5% limit in long term stability. Recently, Viollier[24] reported his findings on the radiometric calibration of the CZCS and proposed an adjustment for CZCS data users. This is significant for the use of wrong calibration data can practically nullify all the efforts devoted into computing the ocean atmospheric radiance.

Another reason that explains the differences in the regression coefficients among the various investigators is that the coefficients are based, in some cases, on statistically small samples. A small sample is often assumed to be less than 30 points. In our cases, only fourteen points were used and since there is significant scatter in the points, a large uncertainty results. Smith's et al early work was based on only 16 points. Also, even though their later work was based on many points, a great number of these were extracted from physically close and homogeneous regions, and since their observations are probably not independent, their sample could be statistically biased. Clark and Gordon's early work was also based on a small sample. The confidence placed on empirically derived numbers is dependent on the size and quality of the data sample. Because of the difficulty in obtaining each of the shipborne sample points, the regression curves of the investigators are based on only a limited number of points and thus have a large uncertainty.

One final note about the empirical relationship between chlorophyll and radiance. The form of the mathematical relationship imposed on the data was a power curve. We believe that a more appropriate relationship would be an exponential curve which have the form of

$$C = a \, \mathrm{Exp} \, (bR_{1,4}) \tag{7}$$

We fit this curve to our data and found that $a = 16.85$ and $b = -1.696$. The value of r^2 was 0.808 versus 0.761 for the power curve and standard errors of regression were relatively small. This form of relationship expresses absorption of light and absorption processes. They usually contain exponential terms in their mathematical form.

In summary, we have described an ocean-atmosphere radiation computation method which can be used to process the multispectral color images of the ocean taken from a high altitude aircraft scanner. The method is applied to derive concentration of chlorophyll-a pigment-bearing phytoplankton. The resulting chlorophyll concentrations were compared with the measurements made by ships stationed along the flight path. The derived empirical relationships between "blue to green ratio" and chlorophyll concentrations from the study show numerical values of 3.0 and -2.4 for coefficients a and b of the chlorophyll concentration expression $C = a(I^w_{431\ nm}/I^w_{550\ nm})^b$. Our values are still considerably different from 1.3 and -1.71 recently reported by Gordon et al but fall fairly near 1.23 and -2.6 reported by Smith and Baker. The large discrepancies which previously existed among investigators are now beginning to show signs of gradual narrowing.

ACKNOWLEDGMENTS

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FIGURES

1. U-2/OCS image of April 16, 1980, off the coast of Jacksonville, FL. The original data was processed and enhanced for ocean chlorophyll gradient expression. The dark filament along the western edge of the Gulf Stream is an upwelling of nitrate rich water and has high chlorophyll content 1.5 to 2.0 mg/M^3.

2. The areal coverage of U-2/OCS in 1980 and ship station locations are shown in solid lines and in solid dots.

3. Aerosol optical depth as a function of wavelength was taken at the SAB (30° N, 80° W) on April 23, 1981. The smooth curve represents the regression fit to the data using the inverted size distribution presented in Fig. 4.

4. Aerosol size distribution obtained by inversion of the spectral optical depth measurements presented in Fig. 3. The straight line represents a Junge size distribution with $\nu^* = 3.0$ which was used in the atmospheric model calculations.

5. Upwelling radiances at 472 nm and 778 nm are shown as a function of aerosol and lower boundary albedo. The modelled curves are for SZA = 56° and a nadir-look sensor at 19.8 km altitude.

6. The 14 data points given in the Table 1 are plotted as the functions of the measured chlorophyll concentration C and the derived ratio products R_{24}. The correlation coefficient for the 14 points was 0.85.

7. Relationship between log C and log (R_{14}). The hatched area represents a range of uncertainty in the estimated coefficient a and b based on the standard error of regression.

8. Chlorophyll concentrations necessary to attain the above spectral curve slopes: a) for $C = 2.96(R)^{-2.4}$ from this study and b) for $C = 0.5(R)^{-1.3}$ from Gordon and D. Clark's early CZCS publication.

9. Spectra of upwelling radiances measured from an aircraft altitude of 305 m by G. Clarke et al in 1968. Estimated regression coefficients a and b based on C, D, and E slopes are 5.4 and - 2.77.

TABLES